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Integrating Census Statistics and Gridded Crop-Water Modelling to Assess Irrigation Requirements and Water Withdrawals in Italy

Reza Eghbali

Dept. of Structural, Geotechnical, and Building Engineering, Politecnico di Torino, Torino, Italy.

*Correspondence should be addressed to Reza Eghbali, Dept. of Structural, Geotechnical, and Building Engineering, Politecnico di Torino, Torino, Italy.; Email: sReza.Eghbali12@gmail.com

ABSTRACT

Agriculture is the dominant consumptive water-use sector in many regions and is increasingly exposed to climate variability, rising food demand, and competition for freshwater resources. This study develops a spatially explicit assessment of agricultural irrigation water use in Italy by integrating official agricultural census statistics, gridded irrigation-area data, and crop-specific irrigation-requirement model outputs. ISTAT 2010 agricultural census data were used to characterize irrigated area by crop, irrigation system, and water source at administrative scale, while the Global Map of Irrigation Areas version 5 (GMIA v5) provided gridded information on irrigated area and water-source attribution. Crop evapotranspiration and irrigation-requirement data were derived from a gridded daily model based on ERA5 climate forcing, crop calendars, and soil-water-balance calculations. Spatial preprocessing, reprojection, rasterization, and crop-category harmonization were performed to align all datasets at a common 0.083333-degree resolution. The integrated framework was applied nationally and to the Piemonte region as a focused case study, comparing the reference year 2010 with the 2005-2014 mean. Results show that total irrigated area estimated from GMIA and ISTAT is highly consistent at province level, with only 0.12 percent difference, although larger discrepancies occur for groundwater because the source categories are not directly equivalent. At national scale, aspersion represents the largest irrigated area, whereas Piemonte is dominated by surface sliding and slide infiltration followed by flooding. The estimated irrigation requirements and withdrawals show lower values in 2010 than the 2005-2014 average, with water withdrawals decreasing by about 15.6 percent in Italy and 23.7 percent in Piemonte. The findings demonstrate that combining official statistics with gridded crop-water modelling can support evidence-based irrigation planning, spatial prioritization of efficiency improvements, and agricultural water-management policies.

Keywords: irrigation requirement; agricultural water use; ISTAT; GMIA; evapotranspiration;

1. INTRODUCTION

Freshwater availability is a central constraint for sustainable food production. Although water is abundant at planetary scale, only a small share is accessible freshwater, and agricultural production competes with domestic, industrial, ecological, and energy-related demands. Irrigation is therefore a key component of food security, but it also represents a major pressure on water resources, particularly in regions where crop production depends on seasonal water supplementation [1,2].

Climate change intensifies this challenge by altering precipitation regimes, increasing evaporative demand, and modifying the timing and frequency of droughts and heat waves. These changes directly affect rainfed and irrigated agriculture through their influence on evapotranspiration, soil moisture, crop growth stages, and irrigation demand [3,4]. For countries in the Mediterranean basin, spatially explicit knowledge of irrigated areas, water sources, and irrigation systems is essential for designing adaptation measures and improving agricultural water productivity.

Italy provides an important case for such an assessment because irrigated agriculture is distributed across contrasting climatic, topographic, and crop-production contexts. The Po Valley and northern regions host extensive irrigated cereal and rice systems, whereas southern regions include large

areas of irrigated vegetables, orchards, citrus, and olive groves. A national assessment therefore requires combining information on administrative agricultural statistics with spatially explicit gridded data and crop-water modelling outputs.

Previous global studies have developed gridded representations of irrigated areas, crop calendars, crop evapotranspiration, water footprints, and irrigation requirements [5-12]. However, the practical use of these products for national or regional planning depends on how well they can be harmonized with official census data and irrigation-system information. Differences in spatial resolution, crop nomenclature, irrigation-source definitions, and temporal reference periods can introduce uncertainty if not treated explicitly.

This article presents a data-integration framework for assessing agricultural irrigation water use in Italy. The framework combines ISTAT agricultural census data, GMIA v5 gridded irrigation-area data, and gridded crop-specific evapotranspiration and irrigation-requirement model outputs. It estimates irrigation requirements by crop, compares irrigated-area estimates between ISTAT and GMIA, calculates irrigation volume by irrigation system, and derives water withdrawals using irrigation-efficiency assumptions. The approach is applied to Italy and to Piemonte as a regional case study.

2. METHODOLOGY

2.1. Study area and analysis periods

The study area covers the full Italian territory using the administrative boundaries adopted by ISTAT. A regional focus is included for Piemonte because the region contains major irrigated agricultural systems, especially rice and maize areas, and because its irrigation-system composition differs strongly from

the national pattern. The main reference year is 2010, consistent with the sixth Italian Agricultural Census. To provide a climatic comparison, the irrigation-requirement model outputs are also summarized as the mean for 2005-2014, while keeping irrigated crop area fixed at the 2010 reference condition.

2.2. Data Sources

Three data families were integrated: official census data, gridded irrigation-area data, and gridded crop-water

model outputs. Table 1 summarizes the function of each dataset in the workflow.

Table 1. Main datasets used in the assessment

Dataset	Main variables used	Spatial / temporal scale	Role in article
ISTAT 2010 Agricultural Census	Irrigated area by crop, irrigation system, and water source	Administrative units down to commune level; reference year 2010	Official reference for crop areas, irrigation systems, and source categories
GMIA v5	Area equipped for irrigation, actually irrigated area,	5 arc-minute global raster grid; reference statistics mainly 2000-2008	Independent gridded dataset for irrigated-area mapping and ISTAT comparison

	groundwater and surface-water shares		
Crop-water model outputs	Crop evapotranspiration, actual evapotranspiration, irrigation requirement, irrigation days	Daily model outputs aggregated to annual values; 0.083333-degree grid	Provides crop-specific water requirement depth for volume calculations
Italian administrative layers and QGIS processing	Province and commune boundaries, rasterized crop and irrigation-system layers	Common grid and projection after reprojection and rasterization	Spatial harmonization and overlay analysis
ISTAT 2010 Agricultural Census	Irrigated area by crop, irrigation system, and water source	Administrative units down to commune level; reference year 2010	Official reference for crop areas, irrigation systems, and source categories
GMIA v5	Area equipped for irrigation, actually irrigated area, groundwater and surface-water shares	5 arc-minute global raster grid; reference statistics mainly 2000-2008	Independent gridded dataset for irrigated-area mapping and ISTAT comparison
Crop-water model outputs	Crop evapotranspiration, actual evapotranspiration, irrigation requirement, irrigation days	Daily model outputs aggregated to annual values; 0.083333-degree grid	Provides crop-specific water requirement depth for volume calculations
Italian administrative layers and QGIS processing	Province and commune boundaries, rasterized crop and irrigation-system layers	Common grid and projection after reprojection and rasterization	Spatial harmonization and overlay analysis

ISTAT is the official Italian statistical source for agricultural census information. The sixth Agricultural Census has a reference date of 24 October 2010 and covers the agricultural marketing year from 1 November 2009 to 31 October 2010. It provides detailed information on land use, agricultural practices, crop areas, irrigation, and other farm characteristics at multiple administrative levels.

GMIA v5 provides gridded layers for the percentage of area equipped for irrigation, actually irrigated area, and the percentage of equipped area irrigated by groundwater, surface water, or non-

conventional sources [13,14]. The GMIA database has a global resolution of 5 arc minutes and is derived by combining subnational irrigation statistics with geographic information on irrigation schemes and land cover.

The crop-water model output used in this study provides daily gridded estimates of crop evapotranspiration and irrigation requirement. The model is based on reference evapotranspiration, crop coefficients, crop calendars, soil-water balance, and climate forcing, and has been applied globally over several decades [15-20].

2.3. Spatial Preprocessing and Harmonization

The ISTAT data were initially available as administrative data and were converted into spatial layers using Italian commune and province boundaries. Vector layers of irrigated area by crop, irrigation system, and water source were rasterized to the common grid used for the crop-water model. The crop-water model outputs were provided in EPSG:4326-WGS84, while some ISTAT spatial processing used EPSG:32632-WGS84/UTM Zone 32. Reprojection and raster alignment were therefore

required before raster multiplication and aggregation.

For GMIA, the raster layers of area equipped for irrigation, actual irrigated area percentage, and source-specific shares were combined to estimate irrigated area by source. The calculations were implemented at cell level as follows:

$$\begin{aligned}
 \text{AAI_GW} &= \text{AAI_pct} \times \text{AEI_GW_pct} \times \text{AEI_ha} \\
 \text{AAI_SW} &= \text{AAI_pct} \times \text{AEI_SW_pct} \times \text{AEI_ha} \\
 \text{AAI_total} &= \text{AEI_ha} \times \text{AAI_pct}.
 \end{aligned}$$

2.4. Crop-Category Harmonization

Crop categories in ISTAT and in the gridded crop-water model are not identical. The harmonization therefore involved direct matching where possible and simplified aggregation where necessary. Grain maize and green maize from ISTAT were combined to match the maize category in the crop model.

Cereals excluding maize and rice were associated with wheat model outputs. Several minor annual crops were matched to average values of annual-crop classes, while fruit, olive, nurseries, and other permanent crops were mapped to permanent-crop categories.

Table 2. Simplified Crop-Category Harmonization Used for Volume Calculations.

Model category used	Corresponding ISTAT category / treatment
Maize	Grain maize + green maize
Rice	Rice
Wheat I and Wheat II	Cereals for grain production excluding maize and rice
Potato	Potato; also used for rape and turnip rape in the thesis workflow
Sugar beet	Sugar beet
Sunflower	Sunflower
Fodder grasses	Other temporary grass; permanent grassland, pastures, and meadows
Grapes	Vineyard
Citrus	Citrus fruit
Another perennial	Olive plantation, fruit plantations, nurseries and other permanent crops
Average annual-crop classes	Dried pulses, textile crops, fresh vegetables outdoor, other arable land crops, short rotation coppices

2.5. Irrigation Requirement and Water-Withdrawal Calculations

The calculation starts from the standard FAO evapotranspiration framework [1]. Reference evapotranspiration ET_0 is converted to crop evapotranspiration ET_c using the crop coefficient K_c . Actual evapotranspiration ET_a accounts for water stress through the stress coefficient K_s :

$$ET_c = K_c \times ET_0$$

$$ET_a = K_s \times ET_c$$

The model estimates irrigation requirement as the minimum water depth required to avoid crop water stress when rainfall and soil moisture are insufficient. To convert the water depth into a crop-specific volume, the irrigation depth was multiplied by the corresponding irrigated area in each grid cell:

$$V = A \times IR$$

where V is the irrigation requirement or crop water requirement volume, A is irrigated area, and IR is

irrigation requirement or crop-water-requirement depth. Irrigation-system volumes were then derived by combining total irrigation-volume grids with the gridded share of irrigated area under each irrigation system.

Water withdrawal from the source was estimated by correcting irrigation volume for field application efficiency. Surface irrigation, including flooding and surface sliding/slide infiltration, was assigned an efficiency of 60 percent; sprinkler/aspersion was assigned 75 percent; micro-irrigation was assigned 90 percent; and other systems were assigned the average of these efficiencies. Thus:

$$\text{Water withdrawal} = \text{Irrigation volume} / \text{field application efficiency.}$$

2.6. Validation and Uncertainty Treatment

Validation focused first on the comparison of total irrigated area between ISTAT and GMIA at commune and province levels. The same comparison was then performed separately for groundwater and surface-water categories. Because ISTAT and GMIA use different source definitions, simplified category matching was required: ISTAT underground water in or near the farm was treated as groundwater, while surface water on the farm, surface water off the farm, and institutional deliveries were treated as surface water. This

assumption is a major source of uncertainty for the water-source comparison.

Additional uncertainty arises from rasterization. Administrative polygons and raster grid cells do not always match exactly, especially when commune areas are smaller than the grid cell or when cell boundaries cut across administrative features. Mixed-pixel effects, edge effects, topological mismatch, and resampling differences can therefore generate discrepancies between crop-based and irrigation-system-based volume totals.

3. RESULTS AND DISCUSSION

3.1. Validation of global models

At national scale, ISTAT reports aspersion as the largest irrigation system by irrigated area, followed by surface sliding and slide infiltration, micro-irrigation, flooding, and other systems. In Piemonte, the pattern is substantially different: surface sliding

and slide infiltration is dominant, followed by flooding. These differences have direct implications for water withdrawal because the dominant systems in Piemonte have lower field application efficiency than micro-irrigation and aspersion.

Table 3. Irrigated area by irrigation system in Italy and Piemonte.

Irrigation system	Italy (ha)	Piemonte (ha)	Interpretation
Aspersion	958,535.14	32,845.90	Largest national share; limited share in Piemonte
Flooding	221,024.76	116,106.34	Moderate national share; major Piemonte system
Micro-irrigation	422,534.39	9,282.45	Important nationally; limited in Piemonte
Other irrigation systems	68,435.53	2,094.81	Smallest share
Surface sliding and slide infiltration	748,390.88	205,929.69	Second nationally; dominant in Piemonte

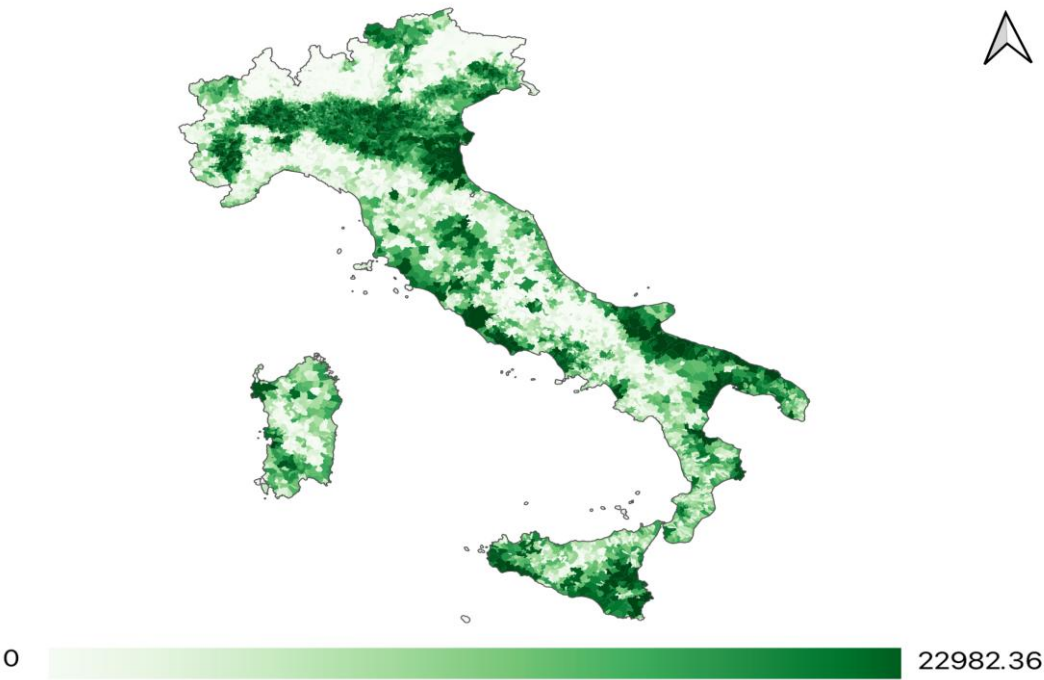


Figure 1. Spatial distribution of total irrigated area by all irrigation systems in Italy.

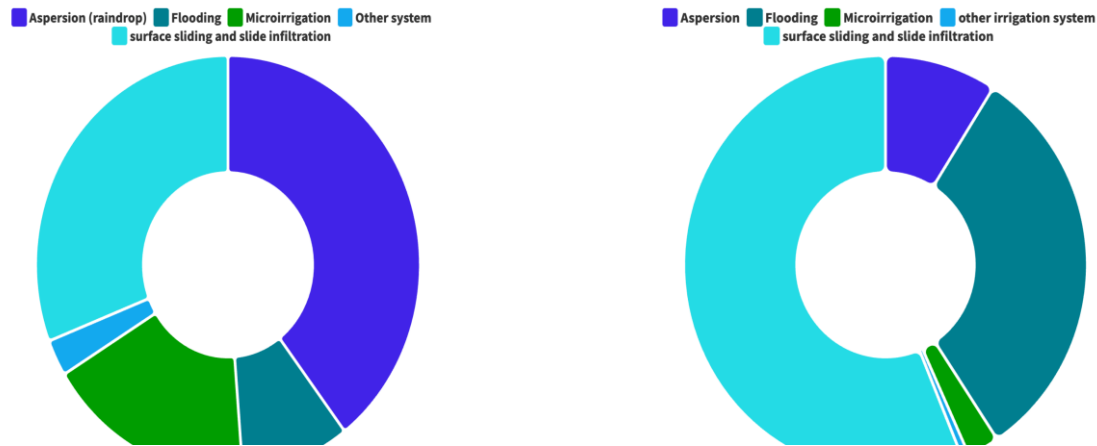


Figure 2. Shares of irrigated area by irrigation system in Italy and Piemonte.

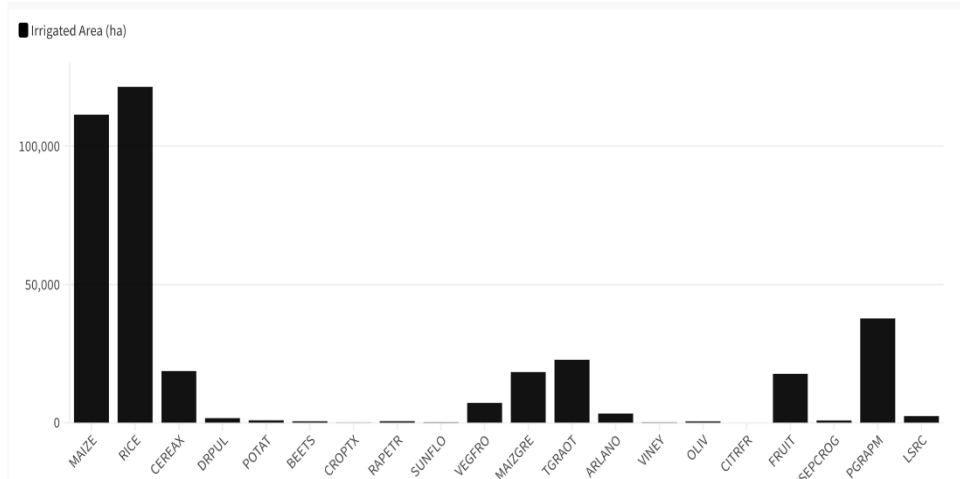
3.2. Irrigated Area by Crop

Crop-area statistics show that maize is the dominant irrigated crop at national scale, while rice is the dominant irrigated crop in Piemonte. The importance of rice in Piemonte explains the large contribution of flooding and surface irrigation

systems to the regional water-withdrawal profile. Other important national crop groups include fresh vegetables, fruit plantations, vineyard, green maize, other temporary grass, permanent grassland, olives, citrus, and cereals excluding maize and rice.

Table 4. Main irrigated crop areas used in the assessment.

Crop group	Italy (ha)	Piemonte (ha)
Grain maize	519,080.76	111,372.70
Rice	245,824.38	121,421.39
Cereals excluding maize and rice	129,870.87	18,716.43
Fresh vegetables outdoor	228,982.00	7,167.53
Green maize	191,148.80	18,318.91
Other temporary grass	185,400.33	22,760.86
Vineyard	176,007.05	179.99
Olive plantation	129,996.21	452.65
Citrus fruit	112,955.71	3.58
Fruit plantations	194,523.61	17,689.36
Permanent grassland, pastures, and meadows	135,839.57	37,701.42



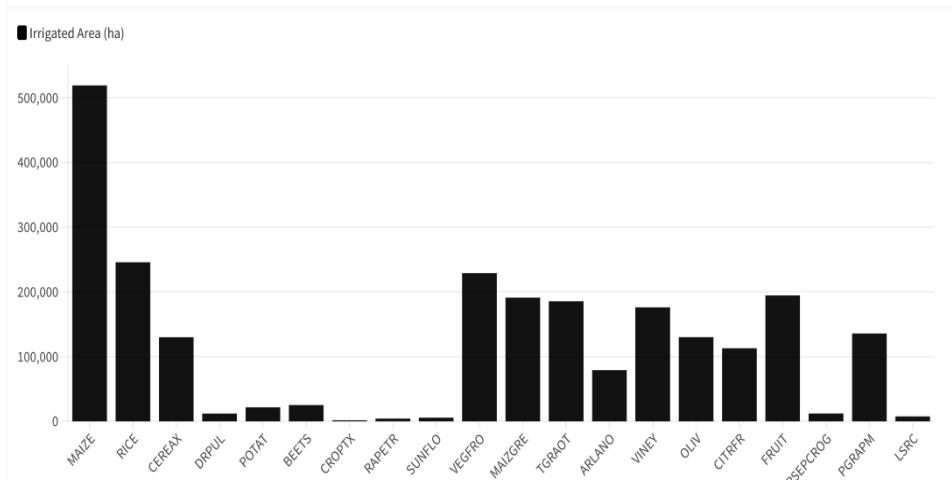


Figure 3. Irrigated area by crop in Italy and Piemonte.

3.3. Comparison Between ISTAT and GMIA Irrigated-Area Estimates

The comparison between ISTAT and GMIA shows a strong agreement for total irrigated area, especially at province level. At province scale, the total irrigated-area difference is only 2,902.46 ha, corresponding to 0.12 percent. At commune level, the total difference is larger, equal to 152,466.90 ha or 5.93 percent. This indicates that aggregation reduces spatial mismatch between the datasets.

Source-specific comparison is less robust. For groundwater, the error is 24.51 percent at commune level and 19.90 percent at province level. For surface water, the corresponding errors are 2.39 percent and 3.31 percent. The larger groundwater discrepancy is consistent with the simplified source-category matching and with the lower GMIA quality rating for irrigation water-source mapping.

Table 5. Comparison of irrigated area estimated from GMIA and ISTAT.

Category	GMIA COM (ha)	ISTAT COM (ha)	Error COM	GMIA PROV (ha)	ISTAT PROV (ha)	Error PROV
Groundwater	816,445.25	616,329.59	24.51%	775,083.67	620,838.93	19.90%
Surface water	1,754,942.30	1,713,028.66	2.39%	1,658,161.31	1,713,028.66	3.31%
Total	2,571,387.60	2,418,920.70	5.93%	2,433,244.99	2,430,342.53	0.12%

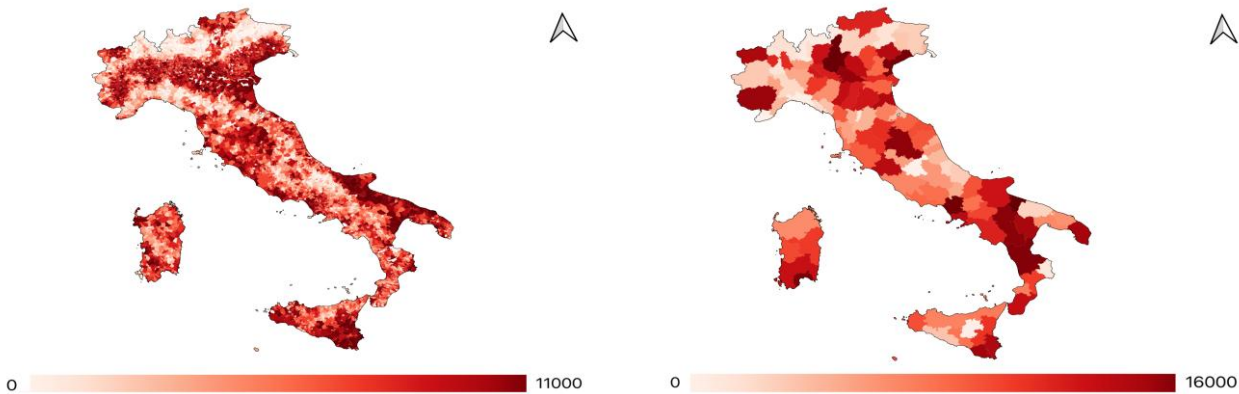


Figure 4. Spatial differences between ISTAT and GMIA irrigated-area estimates at commune and province levels.

3.4. Crop-specific irrigation Requirements

At national scale, olive plantation has the largest irrigation requirement volume in 2010, followed by fresh vegetables outdoor, vineyard, wheat I, maize,

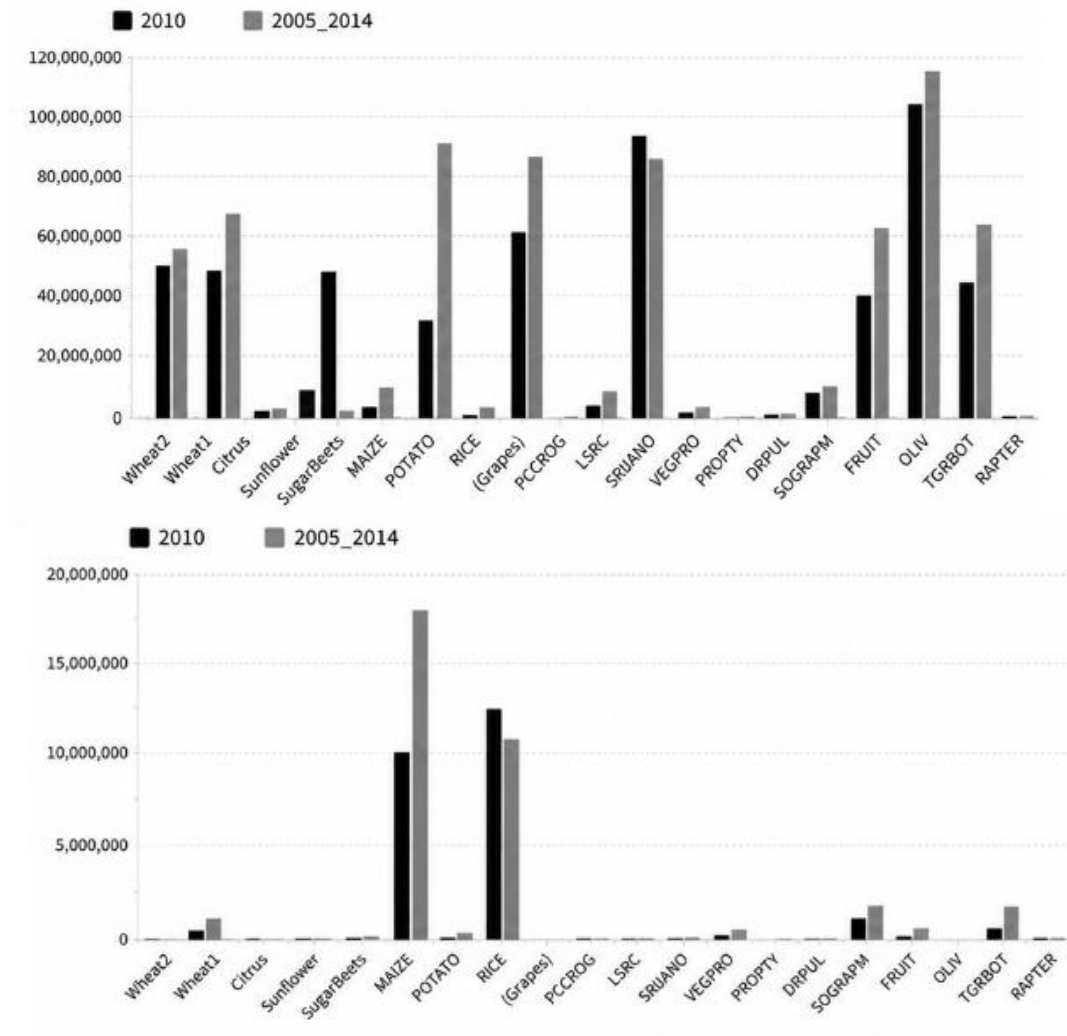
other temporary grass, fruit plantations, and rice. For the 2005-2014 mean, olive plantation remains the largest contributor, followed by vineyard, fresh

vegetables, citrus, other temporary grass, fruit plantations, and wheat I. The national total irrigation requirement is lower in 2010 than the 2005-2014 mean by approximately $7.89 \times 10^7 \text{ m}^3$.

In Piemonte, rice has the highest irrigation requirement in 2010, followed by maize, permanent grassland/pastures/meadows, other temporary grass, wheat I, fresh vegetables, fruit, and potato. For the 2005-2014 mean, maize ranks first, followed by rice,

temporary grass, wheat I, fresh vegetables, and fruit. The regional total is lower in 2010 than in the 2005-2014 mean by approximately $3.27 \times 10^7 \text{ m}^3$.

Because irrigated area is held constant in this comparison, the differences between the 2010 and 2005-2014 results are interpreted primarily as climate-driven differences in evapotranspiration, precipitation, and soil-water conditions rather than changes in crop distribution.



permanent grassland/pastures/meadows, other

Figure 5. Crop-specific irrigation requirement volumes in Italy and Piemonte for 2010 and the 2005-2014 mean.

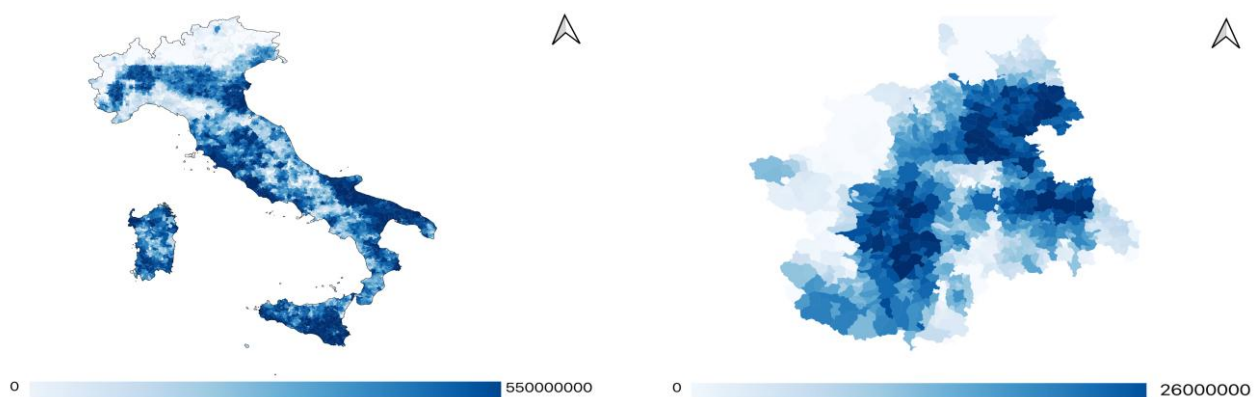


Figure 6. Spatial distribution of irrigation requirement volume in Italy and Piemonte in 2010.

3.5. Irrigation Requirement by Irrigation System

Irrigation-system-based volumes were obtained by distributing the total irrigation requirement according to the rasterized share of each irrigation system. At national scale, micro-irrigation and aspersion dominate the 2010 irrigation requirement

volume, while aspersion is the largest contributor for the 2005-2014 mean. In Piemonte, surface sliding and slide infiltration dominates both the 2010 and 2005-2014 results, followed by flooding.

Table 6. Irrigation requirement volume by irrigation system.

System	Italy 2010 (m3)	Italy 2005-2014 (m3)	Piemonte 2010 (m3)	Piemonte 2005-2014 (m3)
Aspersion	193,932,067.00	240,906,665.10	3,446,922.23	5,445,696.80
Flooding	19,998,745.43	21,920,312.52	10,148,335.54	10,177,459.81
Micro-irrigation	196,346,257.20	227,866,903.90	297,743.36	522,853.74
Other systems	24,563,334.01	27,457,320.66	463,147.41	788,611.17
Surface sliding and slide infiltration	70,777,828.47	81,324,584.92	11,349,715.21	17,027,702.80

3.6. Estimated Water Withdrawal After Efficiency Correction

Water withdrawal is larger than irrigation requirement because of application losses. After efficiency correction, Italy shows the largest 2010 withdrawals for aspersion and micro-irrigation, which together represent about 72 percent of total withdrawals. Piemonte is dominated by surface

sliding and slide infiltration and flooding, which together account for most regional withdrawal. Because these systems have lower assumed field application efficiency, they imply a greater proportional loss than aspersion and micro-irrigation.

Table 7. Estimated water withdrawal by irrigation system after field-application efficiency correction.

System	Italy 2010 (m3)	Italy 2005-2014 (m3)	Piemonte 2010 (m3)	Piemonte 2005-2014 (m3)
Aspersion	258,576,089.00	321,208,886.60	4,595,896.28	7,260,929.05
Flooding	33,331,242.26	36,533,854.09	16,913,892.48	16,962,432.93
Micro-irrigation	218,162,507.70	253,185,448.00	330,825.95	580,948.59
Other systems	32,751,112.09	36,609,760.86	617,529.87	1,051,481.53
Surface sliding and slide infiltration	117,963,047.20	135,540,974.70	18,916,191.90	28,379,504.67

Total water withdrawal decreased in 2010 compared with the 2005-2014 mean by about 15.6 percent in Italy and 23.7 percent in Piemonte. For Italy, the strongest system-level reduction was observed for aspersion, while in Piemonte the strongest

proportional reduction was observed for micro-irrigation. Flooding in Piemonte remained relatively stable, indicating that some traditional irrigation demand patterns are less variable over the examined time periods.

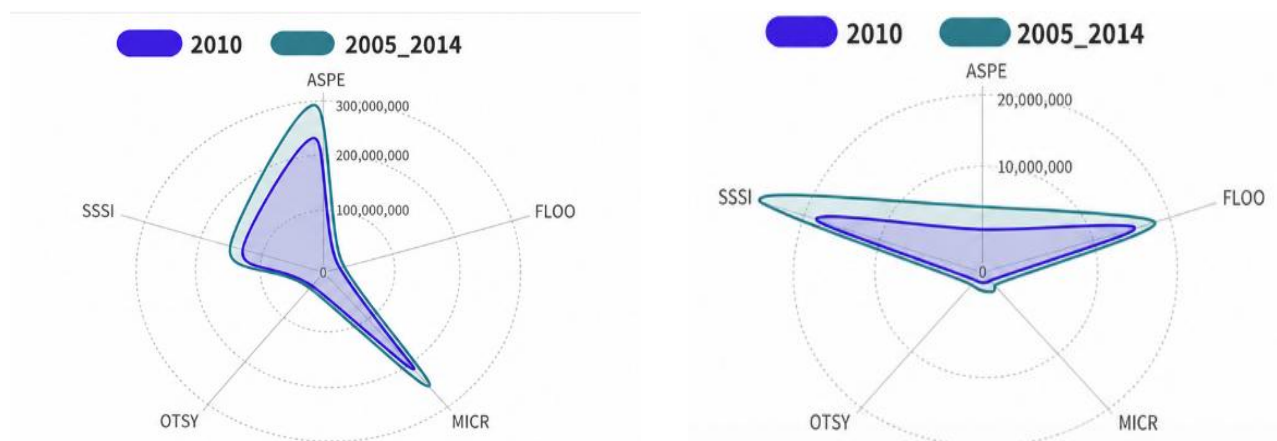


Figure 7. Water-withdrawal volumes by irrigation system in Italy and Piemonte for 2010 and the 2005-2014 mean.

3.7. Crop-specific irrigation Requirements

The comparison between crop water requirement and irrigation requirement clarifies the relative contribution of rainfall and soil moisture. A small difference between crop water requirement and irrigation requirement indicates that most evapotranspiration demand must be supplied by irrigation. In Italy in 2010, textile crops, rape and turnip rape, short rotation coppices, dried pulses, sunflower, nurseries, potato, sugar beet, and rice

show relatively high dependence on irrigation compared with their total crop water requirement. In Piemonte, citrus, textile crops, olive, vineyard, sunflower, sugar beet, rape and turnip rape, and potato are identified as highly irrigation-dependent in relative terms, while maize receives a larger share of its crop water requirement from non-irrigation sources.



Figure 8. Comparison of crop water requirement and irrigation requirement for Italy and Piemonte in 2010.

3.8. DISCUSSION

The results show that official census data and gridded global irrigation data can be complementary. ISTAT provides detailed information on crops, irrigation systems, and water-source categories at administrative scale, while GMIA provides continuous spatial grids suitable for overlay with model outputs. The strong province-level agreement in total irrigated area indicates that GMIA can support spatial analyses in Italy when used for total irrigated-area mapping. However, source-specific attribution should be used more cautiously because category definitions differ and source mapping quality is lower.

The contrast between Italy and Piemonte is important from a water-management perspective. Nationally, aspersion and micro-irrigation account for the largest water-withdrawal shares. In Piemonte, traditional surface methods dominate, particularly surface sliding/slide infiltration and flooding. Because the assumed efficiencies of surface systems are lower than those of micro-irrigation and aspersion, Piemonte loses a higher fraction of withdrawn water before it reaches the crop root zone. This finding supports targeted modernization where technically, economically, and agronomically feasible.

Modernization does not imply a universal replacement of traditional systems. Flooding and surface irrigation may be linked to specific crops, soils, landscape practices, groundwater recharge, and cultural or environmental functions. For example, rice cultivation often requires water-management practices that differ from those used for row crops or orchards. Therefore, efficiency improvement should be assessed together with crop suitability, energy costs, groundwater interactions, drainage, ecosystem services, and farmer adoption capacity.

The comparison between 2010 and the 2005-2014 mean isolates climate-driven variability only partially because the irrigated area is fixed to the 2010 census condition. This assumption is useful for understanding how irrigation requirement responds to meteorological variability, but it does not capture real changes in crop distribution, irrigation infrastructure, cropping intensity, or farmer behavior over time. Future studies could use time-varying crop maps, remote sensing of irrigated area, or updated census information to distinguish climatic effects from land-use and management changes.

The main sources of uncertainty are crop-category harmonization, irrigation-source matching, rasterization, and efficiency assumptions. Crop categories in ISTAT and the model do not perfectly match, and some model values represent aggregated or averaged crop classes. The ISTAT-GMIA source comparison also requires assumptions about the equivalence of institutional delivery categories and surface-water categories. Rasterization errors occur because administrative polygons and model grids are not geometrically identical. Finally, the use of generic irrigation efficiencies provides a first-order withdrawal estimate but does not represent local system performance, conveyance losses, farm-level management, soil conditions, or infrastructure condition.

The workflow identified discrepancies between crop-based and irrigation-system-based volume totals of 6.4 percent for Italy in 2010, 3.2 percent for Italy for 2005-2014, 0.6 percent for Piemonte in 2010, and 3.7 percent for Piemonte for 2005-2014. These values are acceptable for a spatial integration study but should be reported transparently because they quantify the effect of spatial preprocessing and rasterization.

4. CONCLUSION

- This study demonstrates a practical framework for estimating crop-specific irrigation requirements and irrigation-system-related water withdrawals by integrating ISTAT census data, GMIA v5 gridded irrigation-area data, and gridded crop-water model outputs.
- Total irrigated area from ISTAT and GMIA agrees strongly at province level, supporting the use of GMIA for national-scale spatial assessment of irrigated area in Italy. However, source-specific comparisons are more uncertain, especially for groundwater.
- The dominant irrigation systems differ strongly between Italy and Piemonte. Aspersion dominates national irrigated area, while Piemonte is dominated by surface sliding/slide infiltration and flooding.
- Estimated water withdrawals decreased in 2010 compared with the 2005-2014 mean

by about 15.6 percent nationally and 23.7 percent in Piemonte, reflecting climatic differences under the fixed-area assumption.

- Efficiency correction shows that regions dominated by surface systems may lose a larger share of withdrawn water before it reaches the crop root zone, indicating the

importance of targeted irrigation-efficiency improvements.

- Future work should integrate updated agricultural census data, remote sensing of irrigated areas, time-varying crop maps, local irrigation efficiency measurements, and economic assessment of irrigation modernization options.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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